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NASA
SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

WIND LOADS DURING ASCENT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion.

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all previously issued monographs in this series can be found at the end of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, eventually will become uniform design requirements for NASA space vehicles.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was G. W. Jones, Jr. The author was M. E. White of TRW Systems Group/TRW Inc. A number of other individuals assisted in developing the material and reviewing the drafts. In particular, the significant contributions made by J. I. Orlando of McDonnell Douglas Corporation; S. Lutwak of TRW Systems Group/TRW Inc.; and T. V. Cooney, K. G. Pratt, H. B. Tolefson, and D. C. Wade of NASA are hereby acknowledged.

Comments concerning the technical content of these monographs will be welcomed by the National Aeronautics and Space Administration, Office of Advanced Research and Technology (Code RVA), Washington, D. C. 20546.

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1. INTRODUCTION

Loads induced by the wind environment during the ascent phase of flight are of major consideration in design of space-vehicle structure. Maximum inflight wind loads generally occur in the 6- to 15-km altitude region where high dynamic pressures and a severe wind environment combine to induce large lateral shear and bending moments. These wind-induced loads, in combination with loads from other sources, can form critical design conditions for the shroud, forward stages, and interstages, as well as for the aft portion of the vehicle where control forces are applied to maintain stability. Failure to account properly for these loads can result in structural failure.

Wind is the random three-dimensional motion of air. However, only the horizontal winds significantly affect the design of vertically rising space vehicles. These winds exert both direct and indirect forces, of which the following should be considered in the design of the structure:

- Quasi-steady aerodynamic lift and drag forces created by the wind-induced angle of attack.
- Control forces (i.e., either by thrust-vector or aerodynamic-control surfaces) produced by the control system's response to the wind disturbances.
- Inertial forces from the lateral and rotational motion of the space vehicle caused by the quasi-steady aerodynamic and control forces.
- Vibratory forces created by gusts exciting the elastic structural modes and, for liquid-fueled vehicles, the propellant-sloshing modes in the tanks.

The magnitude of these direct and indirect forces depends on the space-vehicle characteristics, the ascent flight-trajectory parameters, and the horizontal wind environment. Significant space-vehicle characteristics to be considered in determining the ascent-flight loads are vehicle geometry, aerodynamics, mass distributions, structural-stiffness distribution, and control-system characteristics. Important ascent-trajectory parameters include the programmed maneuver commands, velocities, accelerations, dynamic pressure, Mach number, and space-vehicle attitudes. Horizontal wind characteristics include wind speed and direction, which vary with altitude, time, and geographical location. All these factors must be properly evaluated to establish the wind-induced loads for structural design.

This monograph treats the determination of wind-induced structural loads on a space vehicle during ascent. In particular, models of the wind environment are described and analytical procedures are outlined for utilizing these models with the space-vehicle properties and trajectory parameters to calculate the wind-induced loads. The wind models are synthesized from measured natural wind-environment data, and these data, available for each of the four major launch sites used by NASA (i.e., Eastern, Western, Wallops, and White Sands), are referenced.

Wind-induced loads for any one altitude cannot be established by considering only the wind-velocity vector at that altitude. The vehicle responses and loads at any altitude are dynamically related to the winds encountered and the maneuvers performed at lower altitudes. Hence, the determination of the wind-induced loads at any altitude requires a trajectory-simulation analysis to obtain the integrated effect of the previously encountered winds and maneuvers.

Since the wind environment at each launch site varies randomly with time, the resulting variation of wind-induced loads is best described statistically. In order to avoid an excessive weight penalty, the design of space-vehicle structure to withstand these wind loads usually allows a slight probability (approximately 5%) that the ascent wind loads could be greater than the design wind loads. As a safeguard against this risk, the winds are carefully monitored prior to each launch and a wind-load validation analysis is made to ascertain whether vehicle wind loads predicted from these winds are less than the design wind loads; if so, the launch is allowed to proceed. However, the prelaunch wind-load validation analysis is not considered in this monograph.

Although ascent wind loads are usually at a maximum in the high dynamic-pressure region, the less severe wind-induced loads at other times during ascent may combine with concurrent lateral loads from programmed maneuvers, buffeting, and staging to form significant design loads. In addition, these lateral loads combine with concurrent axial loads and with internal-pressure force loads to produce an overall loading condition for design.

Other NASA design criteria monographs are closely related to this monograph. The inflight-winds environment monograph in preparation will summarize and reference the wind-environment data at the four major launch sites used by NASA. From such data, analytical wind models can be formulated for the analyses in this monograph. The published monographs cited in references 1 to 4 are concerned with loads from other sources that are encountered concurrently with the ascent-flight wind loads. Another monograph, now in preparation, is concerned with the combination of these concurrent loads for design purposes.

2. STATE OF THE ART

Wind-induced loads on nearly vertically rising space vehicles are determined by analyses which use wind models of the horizontal wind environment and represent the vehicle configuration and vehicle motion. Various wind models and analytical techniques have been utilized in design. Generally, these models and techniques can provide a reasonable assessment of the wind-induced loads. Efforts are continuing, however, to measure and understand more details of the wind environment so as to improve wind models and to utilize expanding computer capabilities to improve analytical techniques.

2.1 Modeling of the Wind Environment

The representation or modeling of the horizontal wind environment for design purposes has depended strongly on the form of the available measured wind data. Most of these data have been obtained by use of the Rawinsonde balloon system, from which the quasi-steady-state wind and the wind shear have been obtained as a function of altitude up to approximately 30 km. The quasi-steady-state wind is defined as the wind vector (i.e., direction and magnitude) and is obtained by averaging measured winds over 600-m height intervals. The quasi-steady-state wind shear is defined as the vector difference between the quasi-steady-state wind vectors established at two altitudes divided by the height interval between them. The Rawinsonde system cannot measure the wind gusts that are the fluctuations of the wind speed about the quasi-steady-state windspeed value within the 600-m altitude interval. Also, the Rawinsonde instrumentation can introduce large inaccuracies in the measurements at high altitudes (refs. 5 to 7).

Newer techniques measure the wind environment in much greater detail than is obtainable with the Rawinsonde system. In particular, the smoke-trail photographic technique (ref. 8) and the FPS-16/Jimsphere balloon system (ref. 9) can measure the wind speed and direction at closer height intervals (25 to 50m) and with greater accuracy. The Jimsphere system has produced a substantial number of measurements of detailed-type soundings for use in vehicle design and operation. The smoke-trail method is more costly and has operational limitations which have prevented rapid accumulation of this type of detailed sounding. With these improved measurement systems, the wind gusts, as well as the quasi-steady-state wind and wind-shear characteristics, can be determined.

2.1.1 Models Derived from Rawinsonde Data

Since Rawinsonde data provide a measurement of the quasi-steady-state wind and wind-shear characteristics, but not of the wind gusts, it has been convenient to model the wind environment and conduct load analyses in two separate phases. In one phase, the quasi-steady-state wind and wind-shear components are modeled for analysis, while the wind gusts are modeled for analysis in the other phase. The loads resulting from each analysis are then combined to represent the total wind-induced load effects. This approach, discussed in the following two sections, has been used in design of most NASA space vehicles and is believed to have provided an adequate assessment of these loads.

2.1.1.1 Quasi-Steady-State Wind and Wind-Shear Models

Although quasi-steady-state wind and wind-shear models, developed from Rawinsonde measurements, have varied throughout the aerospace industry, the modeling of these wind components for structural design applications can be grouped into three categories:

1. Statistical distributions.

2. Samples of measured wind profiles.

3. Synthetic wind profiles.

The statistical-distribution approach (refs. 10 to 12) employs the statistics of the winds (e.g., mean, standard-deviation, or inter- and intralevel-correlation coefficients) together with the analytical models of the vehicle and its motion to predict the statistics of the vehicle loads. This approach requires assumptions of linearity and detailed statistical information on the winds, such as presented in reference 13. This method has not been widely used, probably because the data are difficult to interpret.

Another method of determining vehicle loads induced by the quasi-steady-state wind and wind shear is to calculate the vehicle response and loads from each one of a large sample of actual Rawinsonde wind soundings. The sample is selected over a previous time period (e.g., 10 years) and is assumed to present the environment that could be encountered during the actual launch. This method is believed to produce the most accurate results from Rawinsonde wind modeling. Use of this model is, however, time consuming and requires the handling and processing of a large quantity of data. It has therefore not been generally used for initial design analyses; rather, it has been more suitable for evaluating the final design for launch availability (i.e., the percentage of time that a space vehicle can successfully withstand the loads induced by the ascent-flight winds). However, with the development of faster computers, this approach is coming into wider use. This sample-of-soundings approach has been used in various studies including those reported in references 14 to 17. The data generated by this approach also facilitated studies to assess the persistence of unfavorable winds as related to wind-induced loads, and to construct biased pitch programs that can possibly reduce these loads (refs. 18 and 19).

The most frequently used technique for modeling the quasi-steady-state wind and wind shears is the synthetic wind profile. In this technique, a family of design wind profiles is synthesized from the statistics of quasi-steady-state wind and wind shears at various altitudes. The resultant speed-altitude profiles approximate the measured Rawinsonde soundings, which are the most severe in terms of wind-induced loads. The maximum loads resulting from analyses of the entire family of profiles are then used for design purposes. The advantages of the synthetic-profile approach are that it provides a simple model for load determination in design and serves as a basis for comparisons of vehicle loads in growth and tradeoff studies. The primary disadvantage is that a set of random wind soundings is difficult to represent by a few synthetic profiles.

Many types of synthetic profiles have been used in missile and space-vehicle design (refs. 15 and 20 to 23). These profiles differ in shape and result in different loads on a given vehicle. Furthermore, synthetic profiles have been developed which allow for the effect of a discrete gust added to the quasi-steady-state wind and wind shears. The wind statistics developed by the Marshall Space Flight Center (MSFC) in reference 21 have generally been used by the aerospace industry as the basis for construction of synthetic profiles; and the synthetic-profile representation developed by MSFC from these wind statistics are widely used in the industry. These synthetic profiles may be constructed with or without the discrete gust. A description of the construction of these MSFC profiles is given in the Appendix.

Where a large azimuth capacity for launch is desired, the synthetic wind profiles are generally based on scalar wind-speed profile envelopes (i.e., with no regard to wind direction). Such scalar wind profiles are applied as a head wind, tail wind, and cross wind to determine the most severe loads. Directional wind profiles (i.e., wind based on directional components) have been used in the design of space vehicles that have restricted launch azimuths. The directional profiles are generally less severe than the corresponding scalar profiles and provide a better representation of the wind environment for such vehicles.

2.1.1.2 Gust Models

As previously noted, the Rawinsonde-sounding data do not include the gust characteristics of the wind environment. The horizontal-gust data for the space-vehicle wind-loads analysis have been inferred primarily from the measurements of vertical gusts obtained from horizontally flying aircraft. On the assumption that an isotropic relationship exists, the horizontal gusts were assumed to possess the same characteristics as the vertical gusts (ref. 24).

Gust data thus obtained have been used in the design of most space vehicles. The more recent acquisition of detailed wind soundings has enabled a better definition of the gust content. A spectrum of gusts has been derived by filtering the small-scale motions from the detailed soundings measured at the Eastern Test Range (ref. 21).

Two basic models are used to represent the wind-gust environment: the discrete-gust-shape model and the continuous-turbulence model. The discrete-gust model assumes the gust to have a distinctive shape such as a one-minus-cosine, quasi-square-wave, step, or spike. The gust velocity associated with these shapes has not been established in terms of percentile levels; the velocities used for design applications have ranged from 6 to 15 m/sec. The gust wavelength has been varied or tuned to the vehicle modes to produce the maximum loads. The use of such discrete gusts for design is a rational approach that is frequently employed in the aerospace industry because it is simple and easy to apply.

The continuous-turbulence model is basically a spectrum of the small-scale gust motions that in the past has been obtained from aircraft measurements (ref. 24) and is currently obtained for vertically rising space vehicles from filtered detailed wind soundings (ref. 21). The advantage of the statistical continuous-turbulence model is that it provides a better representation of the higher-frequency gust content than the discrete-gust approach. However, this model has not been widely used in the past because of the lack of good spectral data and because of its complexity. Furthermore, additional detailed wind soundings need to be analyzed to improve this turbulent-spectrum definition for the Eastern Test Range and to obtain similar-type data for the other launch sites.

2.1.2 Models Derived from Detailed Soundings

The most accurate and representative wind model for determining wind-induced loads employs a large sample of detailed wind soundings of the Jimsphere or smoke-trail type. Vehicle loads are determined from each sounding in the selected sample. Since each detailed wind sounding includes both the quasi-steady-state wind and the gust, the resulting loads therefore reflect all the wind characteristics, and a separate gust analysis is not required. This sample-of-detailed-soundings model has received only limited application to date (e.g., ref. 25) since an insufficient amount of detailed soundings has been accumulated to yield a sample that would be representative of all wind frequencies. Furthermore, the use of this model involves the handling and processing of a large quantity of data and requires a complex program for their analysis. However, these shortcomings are being overcome as more detailed soundings are obtained and the expanding capabilities of computers are utilized.

2.2 Vehicle Wind-Load Analysis

2.2.1 Analyses With Rawinsonde Wind Models

As previously mentioned, when Rawinsonde wind data are used, separate wind and gust analyses are performed and the resulting loads are combined to obtain the total wind loads. For each analysis, the vehicle's dynamic responses to these wind loads (e.g., variations in angle of attack, control forces, and accelerations) are initially determined. The most complex part of the analysis is this determination of the vehicle response, which is discussed in the following sections. After the vehicle response is determined, the structural loads at any location along the vehicle are then calculated by a straightforward load-summation technique combining the aerodynamic, inertial, and sloshing forces (ref. 26).

2.2.1.1 Quasi-Steady-State Wind and Wind-Shear Analyses

The vehicle's response and loads induced by the quasi-steady-state wind and wind shears are determined from a rigid-body low-frequency analysis. The analysis consists of a solution of the rigid-body equations of motion considering the externally applied forces of gravity, thrust, control forces, and aerodynamics. Simulation of the vehicle's flight through the wind profile has been accomplished by a digital computer solution of the simultaneous differential equations of motion with time-varying vehicle parameters. There are several methods for making this type of analysis. These methods range in complexity from a single-degree-of-freedom perturbation solution to a many-degree-of-freedom representation that includes complete simulation of the control-system and engine-actuator dynamics (ref. 26).

Many simplified methods have been developed to analyze quasi-steady-state wind and wind-shear effects. The technique developed by Trembath (ref. 10) uses influence coefficients from a series of unit profiles at various altitudes to obtain responses to statistical winds. Hobbs (ref. 27) applies the influence-coefficient concept to obtain bending-moment response to individual wind profiles; Clingan's method of analysis (ref. 28) uses a closed-form solution that neglects the vehicle's rotational motion and considers only perturbations from a reference trajectory; while Van der Maas (ref. 29) uses an alternate form of Clingan's approach by modifying the trajectory equations to a simpler set of perturbation equations for a reference trajectory.

Each of these simplified methods permits a rapid and economical analysis of a large sample of wind soundings. These advantages are offset by a loss of accuracy ranging from 5% to 20%. However, these methods allow a sample of wind soundings to be ranked according to their approximate severity in producing loads on a given vehicle. The soundings identified as critical (i.e., those which can induce high loads) can then be used in a more comprehensive analysis for better assessment of the loads for design. Hobbs' influence-coefficient approach (ref. 27) provides an accuracy within 5% to 10% in loads estimation, and has been widely used in the aerospace industry.

2.2.1.2 Gust Analyses

A separate flexible-body analysis establishes the loads induced by the higher-frequency gust effects. The flexible vehicle is represented by including in the vehicle equations of motion the vehicle structural-bending and propellant-sloshing modes (refs. 30 and 31). The gust analyses are made for critical periods of flight (e.g., transonic, maximum product of dynamic pressure and angle of attack, and maximum dynamic pressure). The vehicle response to the gust is assumed to occur over a relatively short time period so that time-fixed vehicle parameters can be utilized. Both digital and analog computers are used to solve the flexible-body equations. The complexity of these gust analyses depends on the number of degrees of freedom incorporated to represent the vehicle's rigid-body motions, structural-bending modes, propellant-sloshing modes, and control-system dynamics.

For most space vehicles of moderate length, instantaneous gust immersion has been assumed in the gust analyses (i.e., no wind-induced angle-of-attack variations along the length of the vehicle). However, for extremely long vehicles with aft stabilizing fins, such as the Saturn V, a gradual gust immersion has been employed in which the angle of attack varies along the vehicle length in accordance with the distribution of gust velocity as defined by the gust shape. A gust study of the Saturn vehicles indicates that the loads resulting from gradual gust immersion are larger than those obtained from instantaneous gust immersion (ref. 32). Gradual gust immersion has also been significant in the design of vehicles with winged payloads, such as Dynasoar.

2.2.1.3 Combined Wind and Gust Loads

Gust loads are combined with the rigid-body quasi-steady-state wind and wind-shear loads to obtain the total loads induced by the wind environment. Because of a lack of information on the correlation between gusts and wind shears, there is controversy over how to combine these two types of loads. In many analyses, a unity-correlation coefficient has been conservatively assumed and the gust loads have been superimposed on the quasi-steady-state wind and wind-shear loads for each condition analyzed. Marshall Space Flight Center has allowed for correlation of wind shears and gusts by multiplying the wind-shear and discrete-gust values by a factor of 0.85 before the construction of their synthetic wind profiles (ref. 21).

2.2.2 Analyses With Detailed Wind Models

Trajectory-simulation programs have been developed that can be used to calculate the response-time histories of a flexible-body vehicle during its exposure to a detailed (Jimsphere or smoke-trail) wind sounding. These programs employ flexible-body equations of motion, but include time-varying vehicle parameters (e.g., ref. 33). A high-speed digital computer or a complex analog setup (such as described in ref. 24) is required to simulate the entire flight of the vehicle through a sample of these detailed wind soundings and to solve for the responses and loads. Although complex and time consuming to set up, this approach provides the most accurate assessment of the total wind-induced loads.

An influence-coefficient technique (ref. 27) has been applied to the analysis of a sample of detailed-type soundings. The unit profiles, which are derived with a time-varying flexible-body simulation program, include the gust effects and therefore separate gust analyses are not required. This facilitates the rapid and economical analysis of a large sample of detailed soundings. However, this technique has not been evaluated in an actual design. Rather, it has been used to identify the worst-case soundings which are then utilized in a more detailed analysis, such as the one described in reference 24.

2.2.3 Variation of Analysis With Design Phase

The type of wind model and analytical technique selected depends on the design phase. In preliminary design, wind loads are usually determined by a trajectory-response analysis that uses the relatively simple rigid-body perturbation technique with the wind environment represented by synthetic profiles. The additional flexible-body loads resulting from wind gusts are then estimated from the analyst's experience and added directly to the quasi-steady-state wind and wind-shear loads.

As additional and more reliable vehicle characteristics and trajectory data become available, the subsequent models and analyses become more complex. For the final verification of the design loads, a six-degree-of-freedom rigid-body flight-simulation program including the actual control-system dynamics is usually employed to represent the vehicle. A sample of actual Rawinsonde soundings, rather than the synthetic profiles, is used in many of these analyses to represent the quasi-steady-state characteristics of the wind environment. The loads from each sounding are obtained and analyzed to give the quasi-steady-state loads as a function of probability of occurrence. Separate gust analyses, which usually represent the gust with a discrete shape, are conducted to establish the additional gust-induced loads. These analyses are made for each critical point on the trajectory and the loads obtained are added directly to the quasi-steady-state wind and wind-shear loads. The representations of the vehicle in these gust analyses normally consider the planar rigid-body motion, the first three bending modes, the first propellant-slosh mode in each tank, and the control-system and engine-actuator dynamics.

The most rigorous verification of the final design loads employs analyses with a sample of detailed wind soundings together with flexible-body equations of motion and time-varying vehicle parameters, as described in Section 2.2.2.

2.3 Design Considerations

2.3.1 Design Wind Load

Excessive structural weight penalties would result if a vehicle were designed for all possible wind conditions. Accordingly, since the wind environment varies randomly and is represented statistically, normal design practice has been to accept a slight probability (approximately 5%) that the wind loads during ascent flight could at some time exceed the design wind loads. Most NASA space vehicles have been designed to accept this slight risk of possible launch abort.

The design wind loads for most NASA vehicles have been obtained from final analyses using synthetic wind profiles. The wind-speed envelope used to generate the synthetic profiles has a selected probability that the wind speeds will not be exceeded, and loads obtained from the analyses are assumed to reflect that probability. For a few NASA vehicles, a sample-of-soundings model was used. For these vehicles, design wind loads having a selected probability level were obtained from a cumulative load-probability plot of the loads generated by the soundings.

There is no theoretical justification for the assumption that the same probability holds for both wind envelope and loads when the synthetic-profile model is used. However, data on loads obtained by both sample-of-soundings and synthetic-profile methods are available for the Saturn V (ref. 25) and Atlas Centaur (ref. 17), both analyzed for the Eastern Test Range. The results show that the loads from an analysis using a synthetic profile based on a 95-percentile wind-speed envelope were approximately the same as the loads from the 95% level of the cumulative load-probability plot of an analysis using a sample-of-soundings model.

2.3.2 Wind-Load Alleviation

Wind-load-alleviation techniques and corresponding analyses have been developed for reducing the wind loads on space vehicles. For example, reference 17 describes a biased pitch program to decrease the wind-induced angle of attack and thus reduce the wind loads. Biased pitch programs, however, are limited to particular months and to launch sites where the altitude winds are predominantly from one direction. Another type of load-alleviation system is the load-relief autopilot control system which incorporates feedback loops designed to sense excessive lateral accelerations or angles of attack and then command the vehicle to take compensatory maneuvers to alleviate the loads. Reference 34 describes such a system and discusses its application to design.

In the past, load-alleviation techniques have not normally been considered in the design of NASA space vehicles. Such techniques have been used mainly to improve the operational capability of existing vehicles or where modification to an existing vehicle reduced its capability to withstand wind-induced loads. It is quite possible that in the search for more efficient vehicle structure, wind-load-alleviation techniques may be given more serious consideration in future vehicle designs.

2.4 Flight-Test Evaluation

The analytical techniques for determining the vehicle responses and loads are evaluated in some cases by comparison of predicted and flight-measured load data. However, the accumulated flight-test data generally have been inadequate to allow the analyses to be properly evaluated (ref. 4). Comparisons have been made of predicted and flight-measured loads for Saturn (refs. 35 and 36), Atlas/Centaur (ref. 37), Scout (ref. 38), and the individual Minutemen missile flights, such as those presented in reference 39. These comparisons have provided some measure of confidence in the analytical techniques that are presently employed.

3. CRITERIA

The structural loads induced on a space vehicle by the wind environment during ascent flight shall be determined and adequately accounted for in space-vehicle design. The prediction of the wind loads shall use a model of the wind environment in an analysis which incorporates a description of the vehicle structure and flight trajectory. Except where mission requirements state otherwise, the structural design using these predicted wind loads shall allow some probability that the wind loads during ascent flight could at some time exceed the design wind loads. Where practical, ascent wind loads shall be validated by inflight measurements.

3.1 Wind Model

The wind environment encountered during ascent shall be represented by a wind model, formulated from measured soundings of the natural wind, or from wind statistics of these soundings, for use in an analysis to predict the wind-induced loads on the vehicle. Depending upon the design phase, a synthetic-profile wind model with appropriate gust representations, a sample of Rawinsonde soundings with separate gust representations, or a sample of detailed wind soundings incorporating gust information shall be used as the wind model.

3.2 Vehicle Wind-Load Analysis

Analyses to determine the ascent wind loads shall be made during successive design phases of a space vehicle, with the analyses refined by using updated design parameters. Analysis in each design phase shall utilize an appropriately refined mathematical model of the rigid- and flexible-body dynamics and control-system dynamics of the vehicle structure. The analysis shall consider at least the following flight conditions in nominal and perturbed trajectories, as applicable:

- Transition turn
- Transonic regime or regime of maximum aerodynamic buffet
- Maximum $q\alpha$
- Maximum longitudinal acceleration
- Programmed maneuvers
- Staging.

3.3 Design Considerations

To avoid a weight penalty in accounting for all possible wind loads, the structural design shall allow an approximately 5% probability (unless mission requirements permit deviation) that the wind loads could exceed the design wind-load values during the windiest monthly reference period. The final design wind model shall include wind data for flights from all applicable launch sites.

3.4 Flight-Test Evaluation

During development flights of a new or significantly modified space vehicle, the vehicle shall be equipped, if practical, with suitable instrumentation to measure and transmit data that can be used to assess the structural loads induced by the wind environment encountered during ascent.

4. RECOMMENDED PRACTICES

4.1 Wind Models

The complexity of the wind model depends upon the phase of the design. For the initial design, simplified wind models should be used. As the design progresses and more details are obtained on the vehicle configuration and trajectory, then a more complex and representative wind model should be used in the load analyses. The final design analysis should use the most complete and accurate wind model available.

4.1.1 Wind Models for Preliminary Design

It is recommended that the wind model used in deriving preliminary design loads consist of two parts: synthetic wind profiles (without gusts) and separate gusts. Individual analyses should be conducted to determine the loads induced by the synthetic-profile and gust models, and the results should be directly combined to establish the total wind-induced loads.

The recommended synthetic profiles are formulated from the 95-percentile wind-speed envelopes that employ wind statistics based on the "windiest monthly reference period" concept of reference 21. Construction of synthetic profiles is outlined in detail in the Appendix. With this concept, the highest wind speeds are enveloped for each altitude on the profile at the 95-percentile level; that is, with a 5% chance of being exceeded during a one-month reference period, regardless of the month in which they occur. Synthetic profiles constructed from these statistics therefore envelop the most severe wind conditions for any month of the year at the 95-percentile level.

The synthetic profiles should be constructed from scalar (i.e., nondirectional) wind-speed envelopes. These envelopes are identified in reference 21 for all launch sites used by NASA. For vehicles designed to be flown from the Eastern or Western Test Range, where a limited launch azimuth and prevailing wind condition exist, directional wind-speed envelopes (available only for these ranges and summarized in refs. 40 and 41) should be employed. The wind shears to be employed in construction of the profiles for all major launch sites used by NASA are presented in the Appendix.

A family of synthetic profiles should be constructed to represent the complete quasi-steady-state wind environment for the particular launch site to be used. Several profiles should be constructed so that for each one the maximum wind speed occurs at a different altitude in the flight region being investigated. These profiles should also reflect the directional aspect of the winds (e.g., head winds, tail winds, or cross winds). The profiles should be constructed and evaluated in sufficient number to determine the variation of the load responses with the altitude and direction of the quasi-steady-state winds.

The wind gust should be represented by an idealized one-minus-cosine buildup-and-decay wave shape as illustrated in the Appendix. The gust should have an amplitude of 7.65 m/sec and a variable wavelength between 30 and 275 m. This gust representation is applicable for all altitude levels at each of the four major launch sites used by NASA. As an alternate, the spectra of vertical wind-profile details of reference 21 may be used to represent the gust effects. Although these spectra were derived from Eastern Test Range data, they can be assumed to be applicable to all four launch sites and for all altitude levels.

4.1.2 Wind Models for Final Design

The synthetic profiles plus the 7.65 m/sec gust or the spectra of vertical wind profile details, which were previously recommended for preliminary design, may also be used as the wind model in the analysis for final design – except gusts should be considered at all critical portions of the trajectory, as discussed in Section 4.2.1.2. This wind model, when used consistently throughout design, provides a basis of comparison for tradeoff or growth studies.

Although, synthetic wind profiles provide a good approximation of the wind-induced loads, for the final design of those space vehicles that are severely wind-limited, have narrow launch windows, or are man-rated, it is generally advisable to have a more accurate assessment of the wind loads. It is recommended that a "sample of soundings" be employed as the wind model for this analysis – a sample selected from either the Rawinsonde or Jimsphere wind-sounding data accumulations. The Jimsphere soundings contain all the wind characteristics, including gusts; however, if the Rawinsonde soundings are employed, then a 7.65-m/sec gust, as discussed in the Appendix, or a spectra of vertical wind profile details (ref. 21) should also be used in a separate gust analysis in order to obtain the total wind effect.

For a representative sample of wind soundings, it is recommended that a wind sounding be selected for each day during the windiest 30-day "month" of the year at a given launch site. In addition, this sampling should cover a reasonably long period (such as 10 years) to provide a so-called stable sample (ref. 42). The resulting sample of 300 selected soundings should provide a high degree of confidence in the accuracy of the model. Since a 10-year accumulation of detailed Jimsphere wind soundings has not yet been attained, the sampling period should be extended into the adjacent months to produce the desired 300 soundings.

4.2 Vehicle Wind-Load Analysis

At the start of design of a new space vehicle, analyses for loads to be used in the initial structural sizing, weight estimates, and performance evaluations cannot be delayed until all the necessary inputs are available. As a result, it is recommended that the designer use the best information available and employ approximate solutions to obtain loads consistent with the quality of the input data. As the design progresses and more data become available, the analysis should be refined. In particular, the loads used for final design should be determined by a comprehensive analysis which represents the final vehicle structure and examines all significant wind loads along the ascent trajectories. As the vehicle becomes operational, changes in the vehicle mission may require additional analyses to evaluate the final structural design. Analyses are also required for prelaunch wind monitoring to ensure that the wind-induced loads do not exceed design limits; however, these analyses are not covered in this monograph.

4.2.1 Preliminary Design Analyses

4.2.1.1 Quasi-Steady-State Wind and Wind-Shear Loads

Preliminary load analyses should begin with the calculation of loads for the maximum $q\alpha$ flight condition, which usually produces the critical design loads. A three-dimensional trajectory-simulation program should determine the vehicle's response to head winds, cross winds, and tail winds. Only the simplest representation of the control system, including the best available attitude and rate gains, is needed for this phase of analysis. If the control-system design gains are not available, then a unity-control system should be incorporated. This control system always keeps the vehicle in a trimmed condition (i.e., with no rotational acceleration). A perturbed (i.e., off-nominal) trajectory is recommended for use in this analysis to account for possible vehicle-parameter dispersions that can influence the loads. The perturbed trajectory can be established by varying the vehicle characteristics. For example, the programmed pitch rates can be increased or an upper tolerance on the thrust and a lower tolerance on the aerodynamic drag can be incorporated. Introduction of these perturbations normally results in a more severe dynamic-pressure environment and hence in conservative wind loads.

4.2.1.2 Gust Loads

Flexible-body gust-load analyses need not necessarily be conducted in the initial design studies of the lower propulsive stages of large booster vehicles. The loads induced in these flexible bodies may be estimated from studies of similar vehicles. For these lower stages of most booster vehicles (e.g., Atlas, Titan, or Saturn), the lateral loads derived from the rigid-body flight simulation should be increased by 20% to account for the additional flexible-body gust loads. The flexible-body gust loads, are, however, more significant for the design of large flexible payloads that are mated on top of the booster vehicles. The flexible-body gust loads for such payload configurations can be of nearly the same magnitude as the rigid-body loads, as was the case for the Apollo spacecraft configuration (ref. 42). It is therefore recommended that a gust analysis be conducted for initial studies of such flexible payload configurations.

A gust analysis, if deemed necessary for preliminary design, need only be conducted for the time of maximum $q\alpha$ and should employ time-fixed vehicle parameters. An appropriate dynamic model would include at least the first two lateral bending modes. The higher modes generally contribute little to the total gust load and can be neglected during this phase of analysis. Sloshing modes can be included, but they are primarily important for stability analyses and do not generally induce significant structural loads (ref. 26). In the analysis, the gust should be applied normal to the vehicle's longitudinal axis and the vehicle should be assumed to be instantaneously immersed in the gust. Additionally, the gust wavelength should be varied to determine the maximum load response. Gust loads should be determined for each plane of asymmetric space vehicles. The resulting flexible-body gust loads should be superimposed directly on the quasi-steady-state wind and wind-shear loads to obtain the total loads induced by the wind environment.

4.2.2 Intermediate and Final Design Analyses

As the design proceeds beyond the preliminary phase, it is recommended that the vehicle model be refined, the input data be improved, and more detailed load analyses be conducted. Consideration should be given to analyzing other flight conditions that are influenced by the wind environment, including the transition-turn, transonic, and staging conditions. The transition-turn and transonic conditions are analyzed in the same manner as the maximum wind response (i.e., by conducting a flight simulation up to the altitude of the desired flight condition). However, at staging altitude, the angle of attack attributed to the drift of the vehicle is quite small and can be neglected; thus, a flight simulation is not necessary. The maximum wind-velocity vector at that altitude should be combined directly with the vehicle's velocity vector to determine the wind-induced angle of attack and the resulting loads.

The final design configuration should be analyzed in detail. All flight conditions influenced by the wind environment (Sec. 3.2) should be examined to determine the final wind-induced loads. The supporting computer programs should include all available detail. For quasi-steady-state wind loads on symmetric vehicles, the digital flight-simulation program should employ at least five rigid-body degrees of freedom (no rolling). The rolling degree of freedom should be incorporated for asymmetric vehicles, especially vehicles with a winged payload, tail fins, or strap-on solids. Only a low-frequency type of autopilot need be included for this rigid-body analysis of the flight. The final gust-load analysis should again employ time-fixed vehicle parameters and include at least two rigid-body degrees of freedom (translational and rotational), three structural bending modes, and complete control-system dynamics and engine dynamics. Gradual gust immersion should be included for space vehicles with a winged payload or large aft stabilizing fins.

A nominal trajectory should be used in the final analysis to determine the wind-induced loads. However, dispersions and tolerances of the vehicle parameters and the atmospheric properties other than winds have an influence on the trajectory and loads. The additional incremental loads resulting from each of the dispersed parameters should be determined by separate trajectory simulations. In determining these additional loads, consideration should be given to dispersion and tolerances of vehicle and atmospheric parameters. Vehicle parameters include aerodynamic characteristics, pitch-programmer rates, thrust, weight, and center of gravity. Atmospheric parameters (e.g., density and pressure) differ at each launch site (refs. 43 to 46). A consistent level of deviation (such as $\pm 2\sigma$) should be used in each analysis. These deviation loads are independent and random; therefore, the individual dispersion loads should be root sum squared along with the buffeting and gust loads to derive the total lateral loads from random effects. This total random load should be superimposed on the quasi-steady-state wind and wind-shear loads to establish the inflight wind design loads.

The preceding analytical techniques should be used to assess the synthetic wind profiles plus the 7.65-m/sec gust or the spectra representation of vertical wind-profile details. If a sample-of-Rawinsonde-soundings model is used, the influence-coefficient technique (ref. 27) should be used to determine the quasi-steady-state wind-induced loads for each sounding. This technique requires that the 7.65-m/sec gust be separately analyzed. The total loads resulting from the sample-of-soundings and gust analyses are combined into cumulative probability plots which will enable the structural load to be identified for various probability levels. The particular wind soundings that induce loads near the 95% probability level should then be analyzed again, but with the more comprehensive digital-simulation program so as to provide the refined assessment needed to obtain the design wind load at the 95% probability level.

An alternate wind-loads analysis recommended for final design of major vehicles with complex structure utilizes a sample-of-detailed-soundings model together with flexible-body equations of motion and time-varying vehicle parameters (ref. 33). A high-speed digital or analog computer setup (ref. 24) should be employed to compute the resulting wind loads, which reflect all the wind characteristics. These loads should be statistically analyzed to identify the structural loads for the 95%-probability level.

4.3 Design Considerations

4.3.1 Design Wind Load

In the wind-load analysis for the final design, if the wind model is the synthetic profile described in the Appendix combined with gust or spectra representation (Sec. 4.1.2), the maximum loading obtained should be used as the design wind load. If a sample-of-soundings wind model is used, the design wind load should be the loading with a 95% probability of not being exceeded, taken from the cumulative load-probability plot.

4.3.2 Wind-Load Alleviation

It is recommended that the use of wind-load-alleviation techniques, as described in references 17 and 34, be considered for the following circumstances:

- Where there is a need to improve the launch availability of an existing or modified space-vehicle system.

- Where it is desired to design a vehicle for the utmost structural efficiency, particularly if the mission requirements are to launch only from launch sites where the altitude winds are primarily from one direction.

If such load-alleviation techniques are to be considered in structural design, studies should be initiated as early as feasible so that the possible load reductions can be considered in structural design. In any case, where load-alleviation techniques are used, the analytical techniques and applications of wind data in the comprehensive analyses described in Section 4.2.2 should be followed.

4.4 Flight-Test Evaluation

Space vehicles in the development phase should be equipped with measuring devices to assess structural loads induced by the wind environment. The instrumentation for such measurements is identified in reference 4. Since development flights are made under carefully controlled wind conditions and may occur during months with only moderate winds, it may be necessary to introduce special pitch maneuvers or pitch programs to simulate a more severe load environment (ref. 39) that more nearly approximates the design wind loads. The measured data will provide an assessment of both the analytical procedures employed and the adequacy of the structural design of the space vehicle.

APPENDIX
CONSTRUCTION OF SYNTHETIC PROFILES AND GUST SHAPES BASED ON 95-PERCENTILE WIND-SPEED ENVELOPES

A.1 Synthetic Wind Profiles Without Gust

The construction of synthetic wind profiles employs steady-state wind-speed envelopes and wind-speed changes with altitude (i.e., wind shears). The 95-percentile envelopes are used for a given launch site and launch azimuth and are obtained as specified in Section 4.1.1 of this monograph. The wind-speed changes for these 95-percentile synthetic profiles are identified in tables I and II, and are applicable to all launch sites and all launch azimuths.

TABLE I. – ADJUSTED* 99-PERCENTILE BUILDUP WIND-SPEED CHANGES AT TOP OF ALTITUDE LAYERS FOR VARIOUS SCALES OF DISTANCE

Wind speed at top of altitude layer (m/sec)	Scale of distance (m)									
	5000	4000	3000	2000	1000	800	600	400	200	100
	Wind-speed changes (m/sec)									
⩾90	64.4	62.1	59.9	53.5	36.6	31.9	27.2	22.4	15.7	7.6
80	60.1	59.1	57.0	50.0	34.3	30.2	25.8	21.0	14.4	7.6
70	52.9	52.4	51.3	46.2	32.5	28.6	24.6	19.7	13.2	7.6
60	46.8	46.3	45.5	40.8	30.3	27.3	23.2	18.5	12.2	7.6
50	40.3	39.8	39.0	36.1	28.4	25.5	21.7	17.0	11.5	7.6
40	32.7	32.0	31.3	29.7	23.6	21.1	18.0	14.5	10.3	7.6
30	23.8	23.4	22.5	20.8	17.7	16.3	14.6	12.3	9.5	7.6
20	15.7	15.1	14.9	14.2	13.1	12.2	11.3	10.0	8.5	7.6

TABLE II. – ADJUSTED* 99-PERCENTILE BACK-OFF WIND-SPEED CHANGES AT BOTTOM OF ALTITUDE LAYERS FOR VARIOUS SCALES OF DISTANCE

Wind speed at bottom of altitude layer (m/sec)	Scale of distance (m)									
	5000	4000	3000	2000	1000	800	600	400	200	100
	Wind-speed changes (m/sec)									
⩾90	66.5	63.2	57.8	50.4	37.2	33.3	29.1	24.2	15.7	7.6
80	60.5	58.3	54.2	47.6	34.8	31.6	27.6	21.9	14.0	7.6
70	54.4	51.9	49.2	44.2	33.0	29.3	25.3	20.1	12.8	7.6
60	47.6	46.5	44.4	40.3	30.6	27.2	23.0	17.8	11.8	7.6
50	40.4	40.0	39.3	37.2	28.0	24.6	21.1	16.5	11.0	7.6
40	33.2	32.3	31.4	30.0	25.1	22.5	19.5	14.8	10.1	7.6
30	26.0	25.5	25.0	22.9	19.2	17.5	15.3	12.7	9.4	7.6
20	15.3	14.9	14.2	13.3	12.1	11.5	10.6	9.8	8.4	7.6

*Wind-speed changes adjusted to 0.85 times 99-percentile values to allow for correlation of 99-percentile combined gust and shear.

APPENDIX

As shown in figure 1, the following steps should be taken to construct each 95-percentile synthetic profile:

1. Select the scalar 95-percentile wind-speed envelope for the particular launch site (ref. 21) for application as a head wind, tail wind, or cross wind. If the vehicle is to be designed for severely restricted launch azimuths, the applicable 95-percentile directional wind profiles (refs. 40 and 41) may be used. If a directional profile is used to construct, for example, a tail-wind profile for a 90° launch azimuth, the 270° wind-speed envelope must be used.

2. Select an altitude level (h_p) at which it is desired that the synthetic profile reach its peak wind speed. This may be any altitude level in the particular flight region being investigated. At this selected altitude level, label the corresponding wind-speed envelope value, V_p.

3. Construct the wind-buildup curve. Using the peak wind-speed value (V_p), select from table I the wind-speed changes for various scales of distances. These scales of distances are referenced to the altitude level of the peak wind. For example, assume the peak wind speed is 70 m/sec at an altitude of 14 km. At a scale of distance of 100 m below the h_p level, the wind speed decreases by 7.6 m/sec. Thus, a data point is plotted at an altitude of 13.9 km (i.e., 14 km −100 m) and at a wind speed of 62.4 m/sec (i.e., 70 m/sec −7.6 m/sec). The next data point is at 13.8 km (14 km −200 m) and at a wind speed of 56.8 m/sec (70 m/sec −13.2 m/sec). This procedure is continued for scales of distances up to 5000 m below the altitude of peak wind. A curve drawn through these data points results in the wind-buildup curve.

4. The extension of the wind-buildup curve back to the surface level is constructed by a straight line from the origin (i.e., zero altitude and velocity) to a point where this line merges tangentially into the wind-buildup curve.

5. The extension of the synthetic profile above the altitude level of peak wind is constructed by allowing the profile to follow the wind-speed envelope. An alternate method of extending the profile above the altitude of peak wind is to construct a back-off wind shear using data of table II in the same manner that table I data were used for the wind buildup curve. In either method, the profile should be terminated at an altitude level that is 5000 m above the h_p level.

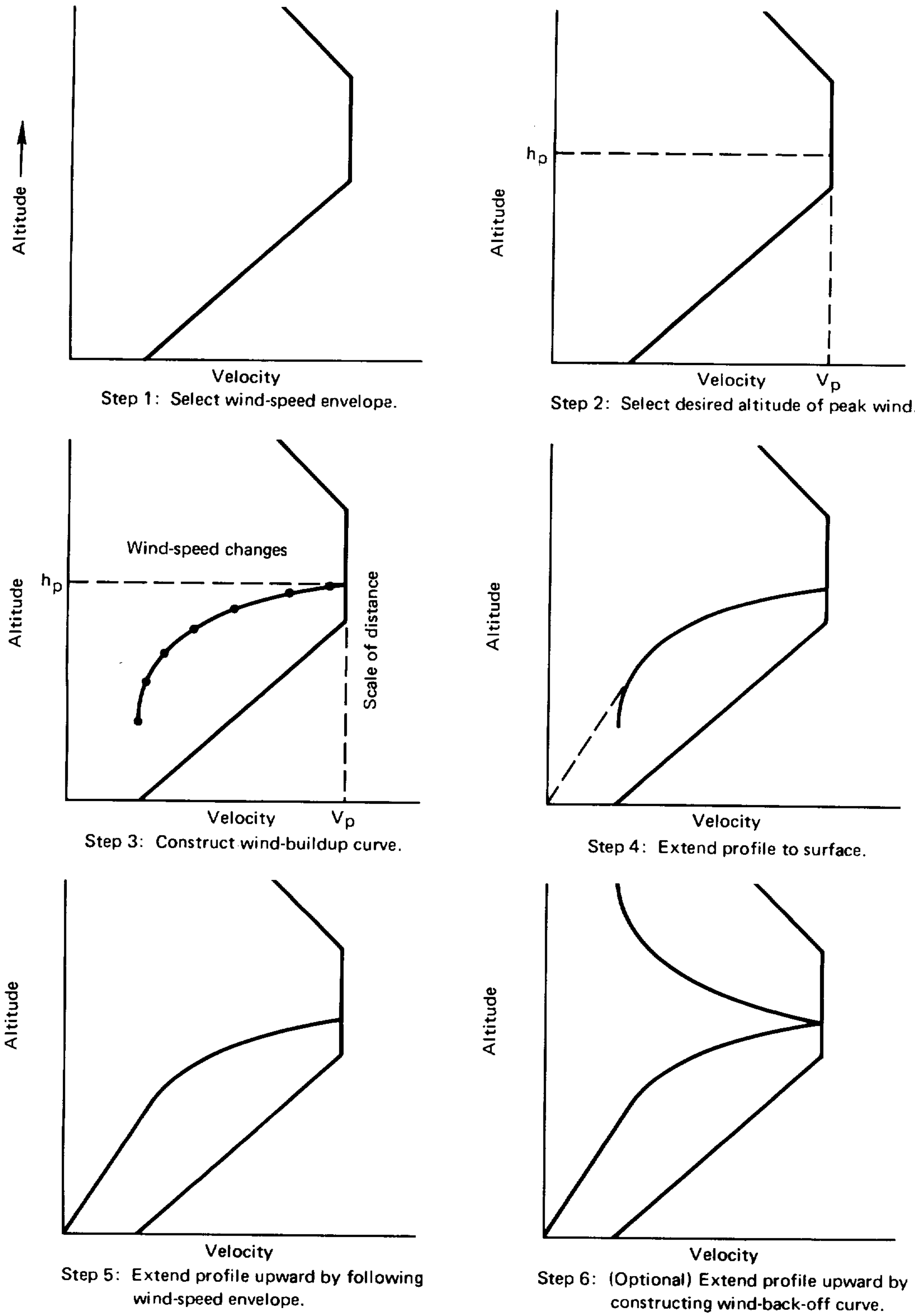

Figure 1. – Construction of synthetic profile (without gust).

A.2 Synthetic Wind Profiles With Gust

The wind gust may be superimposed on the synthetic wind profile. The wind gust should be represented by an idealized one-minus-cosine buildup-and-decay wave shape with a constant velocity plateau inserted at the wave peak, as illustrated in figure 2. The gust should have an amplitude of 7.65 m/sec and a variable thickness (th) between 30 and 275 m. The 7.65 m/sec gust is taken from measured 9 m/sec imbedded-gust maximums multiplied by 0.85 factor to allow for less than unity correlation between gusts and wind shears. The thickness of the gust is defined by the altitude difference of the inflection points of the buildup and the tail-off curves. In figure 2, the gust profile is superimposed on the synthetic wind profile at the altitude of peak wind. The gust profile consists of the following four segments identified in figure 2: (1) a linear extension of the shear buildup; (2) the buildup to the peak gust speed by a one-minus-cosine curve with a half wavelength of 30 m altitude; (3) a constant velocity plateau; and (4) the tail-off, which is the second half of the one-minus-cosine wave.

Referring to the point, 0, where the shear buildup intersects the wind-speed envelope (fig. 2), the gust is described by the following equations (ref. 21):

$$0 \leqslant \Delta H \leqslant a_2 \qquad \Delta W_G = 0.765 \Delta H \tag{1}$$

$$a_2 \leqslant \Delta H \leqslant 30 - a_1 \qquad \Delta W_G = 3.825 \left\{1 - \cos\left[\frac{\pi}{30}(\Delta H + a_1)\right]\right\} \tag{2}$$

$$30 - a_1 \leqslant \Delta H \leqslant th - a_1 \qquad \Delta W_G = 7.65 \tag{3}$$

$$th - a_1 \leqslant \Delta H \leqslant th + 30 - a_1 \qquad \Delta W_G = 3.825 \left\{1 - \cos\left[\frac{\pi}{30}(\Delta H + 30 + a_1 - th)\right]\right\} \tag{4}$$

$$th + 30 - a_1 \leqslant \Delta H \qquad \Delta W_G = 0 \tag{5}$$

where ΔH is the altitude difference (m); ΔW_G, the gust wind speed (m/sec); a_1, the altitude shift in meters of the one-minus-cosine buildup curve required to a tangential changeover from the shear buildup envelope and the gust; a_2, the altitude distance in meters between point 0 and the tangent point of the shear buildup envelope and the gust; th, the "thickness" of the gust in meters (defined as the altitude difference between the inflection points of the one-minus-cosine gust buildup and tail-off portions of the gust envelope curve); and a_1 is 0.9215 m, and a_2 is 0.9137 m.

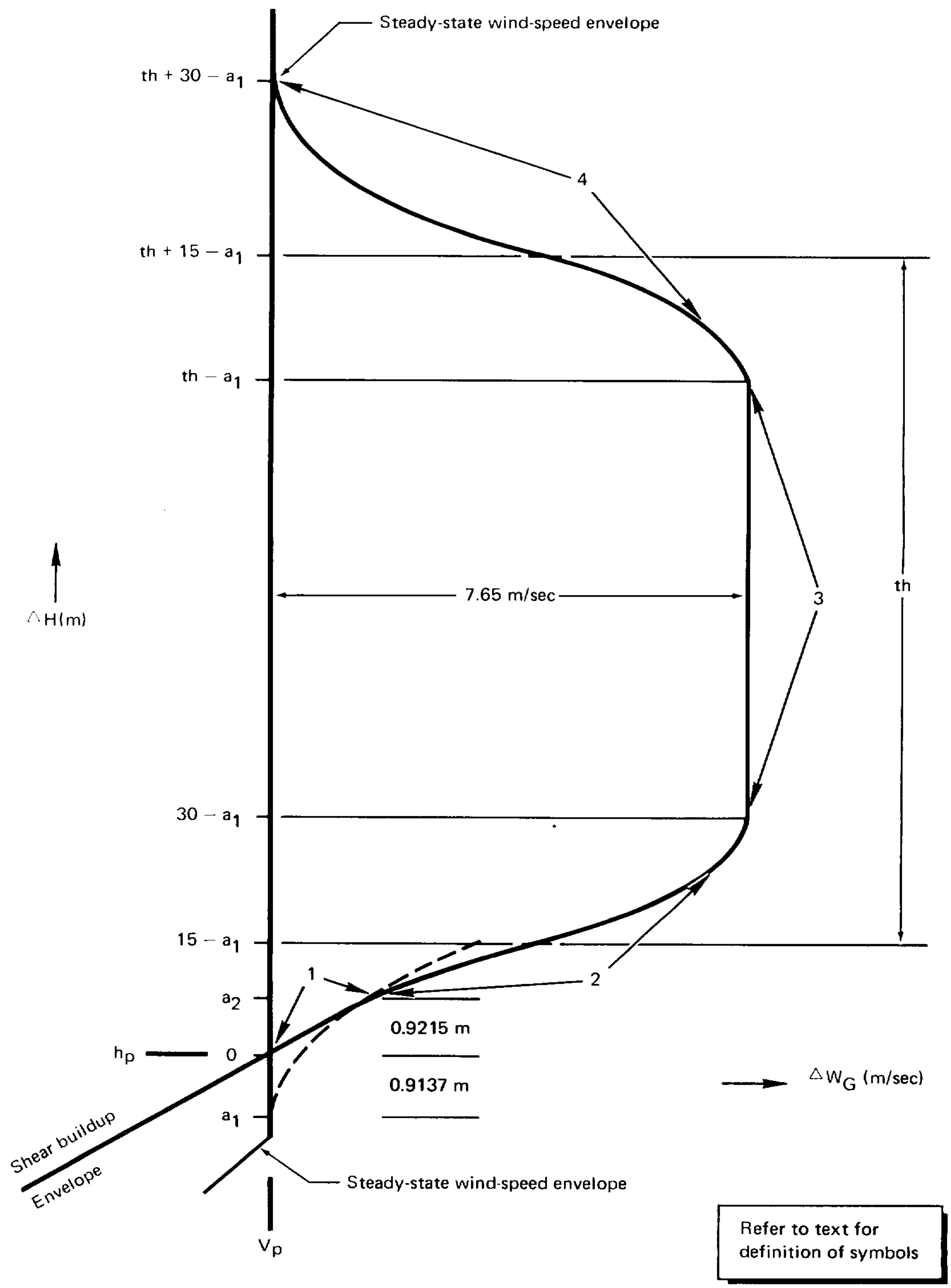

Figure 2. – Relationship between gust shape, steady-state wind-speed envelope, and wind-shear buildup.

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SP-8002	(Structures)	Flight-Loads Measurements During Launch and Exit, December 1964
SP-8003	(Structures)	Flutter, Buzz, and Divergence, July 1964
SP-8004	(Structures)	Panel Flutter, May 1965
SP-8005	(Environment)	Solar Electromagnetic Radiation, June 1965
SP-8006	(Structures)	Local Steady Aerodynamic Loads During Launch and Exit, May 1965
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